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Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

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CRETACEOUS TECTONIC COMPLEX, ST. CROIX

Robert Speed
Department of Geological Sciences
Northwestern University
Evanston, IL 60208

James Joyce
Department of Geology
University of Puerto Rico
Mayaguez, PR 00708

ABSTRACT

A tectonic complex of Cretaceous sedimentary rocks underlies St. Croix, possibly to substantial depth. The sedimentary rocks are almost entirely volcanigenic, derived from contemporaneous arc volcanoes in the duration, Cenomanian or Turonian through Maastrichtian. Minor pelagic beds (chert) also occur. All the volcanigenic sedimentary rocks are deep marine and can be assigned to turbidite facies from outer to inner fan. The depositional site was a basin floor near the base of slope of a Late Cretaceous island arc whose duration of activity was at least 14 ma and perhaps, greater than 30 ma. The basin may have been a trench floor. The tectonic complex in which all the Cretaceous strata occur is an assembly of thrust sheets (= nappes). Beds in all the sheets were folded and cleaved to varied degrees and in varied sequences before a short episode of late Maastrichtian igneous intrusion. Early deformations are S- to SW-verging. The tectonic complex is interpreted as a product of accretion during Late Cretaceous convergence in which the downgoing plate had a component of N to NE transport in today's coordinates.

INTRODUCTION

Cretaceous sedimentary and intrusive igneous rocks underlie all of St. Croix's surface except for a central region of unconformable Miocene and younger cover (Fig. 1). The depositional realms and pre-Miocene structural evolution of the largely volcanigenic Cretaceous strata are the focus of this paper with the aim of understanding the early tectonics of St. Croix. Our field work in St. Croix was in the middle seventies and 1988; some of these results are Speed (1974), Joyce (1979), and Speed et al. (1979). Earlier publications providing data on the Cretaceous rocks were Quin (1907), Cedarstrom (1950), and Whetten (1966), and a later one by Stanley (1988). Our studies focused more closely on outcrop-scale structural analysis, structural synthesis, and dating than those of other workers and had the benefits of advances in turbidite facies analysis.

The magmatic character of St. Croix's Cretaceous intrusions and the metamorphism of Cretaceous sedimentary rocks are important facets of St. Croix's early evolution not dealt with this paper. Whetten (1966) provides discussions on these subjects.

ARCHITECTURE OF ST. CROIX

The island of St. Croix is a peak on the submarine St. Croix platform which is a bathymetric ridge and probable extensional fault block in the southeasternmost Greater Antilles. At the surface, St. Croix is underlain by Cretaceous sedimentary rocks that occupy a Cretaceous tectonic complex, Cretaceous igneous intrusions, and Cenozoic strata (Fig. 1).

The Cretaceous tectonic complex is composed of folded, cleaved, and faulted sedimentary rocks of Cretaceous depositional ages. Our studies to date indicate that strata of the complex are probably not in a depositional succession. Rather, the complex may be an assemblage of tectonic sheets or nappes, each bounded by shallowly dipping faults that we interpret to be thrusts. Figure 1 shows the six nappes (K1-6) identified to date. Differentiation of the nappes is based on differences in stratal character and structural sequences given in Table 1. Their fault contacts are exposed in isolated outcrops, and most of the nappe boundary traces in Figure 1 are interpolated below extensive vegetation and Recent cover. Future work may show that these large nappes are divisible into smaller fault-bounded units.

Igneous intrusions at least partly of Maastrichtian age occur as dikes and sills throughout the tectonic complex and as plutons, one in western and the other in eastern St. Croix (Fig. 1). These appear to be a consanguinous suite, judged petrographically to be of island arc magma. Some dated intrusions followed the main assembling of the tectonic complex, thus proving the complex is Cretaceous. Other intrusions, mainly sills, were folded and (or) cleaved in early deformations. These pre- and syncomplex intrusions are not yet dated radiometrically and are known only to be postdeposition, hence Late Cretaceous.

The Cretaceous tectonic complex and Cretaceous intrusions may extend to substantial depth because similar igneous and metasedimentary rocks have been dredged off the north flank of St. Croix at depths of 1.5 km (Bouysse et al., 1985) and because a refraction layer with velocity of about 4.7 km/sec extends from the surface of St. Croix to a depth of about 8 km (Officer et al., 1987).

The central region of St. Croix is underlain by little deformed Cenozoic sedimentary cover (Fig. 1) (Gill, 1989). The cover occupies a deep basin that may be a full graben as shown on Figure 1. Cenozoic strata unconformable on Cretaceous rocks at the basin flank are as old as middle or early Miocene (Multer et al., 1977) but could be pre-Miocene in the deeper reaches of the graben (Whetten, 1966; Lidz, 1988). The Miocene and Pliocene normal faulting associated with subsidence of the graben is probably related to regional extension that has developed the St. Croix platform and adjacent basins.

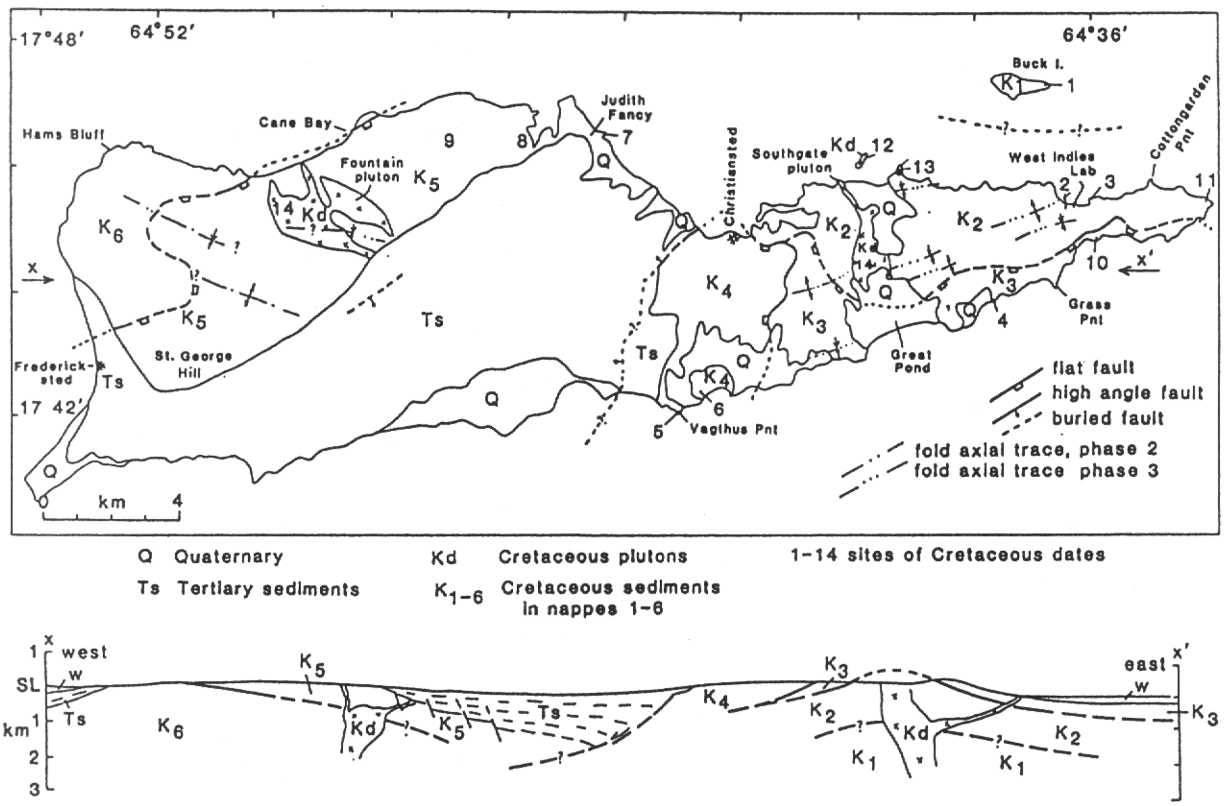

Figure 1. Map of St. Croix showing outcrop areas of Cretaceous and Cenozoic rocks, nappes K1-K6 of Cretaceous rocks, diagrammatic cross section, axial traces to some macroscopic folds, and sites of samples dated by fossils or KAr (Table 2).

CRETACEOUS LAYERED ROCKS

Introduction: The Cretaceous layered rocks of St. Croix are almost entirely volcanigenic sediments together with minor pelagic sediment that accumulated in subwavebase, probably deep marine sites. There are no lavas or proved pyroclastic deposits, contrary to claims by Lidz (1988).

Each of the nappes of the Cretaceous tectonic complex probably or possibly contains a coherent stratigraphy (K2, K4, K5 are probable, others possible), but correlations cannot be made between adjacent nappes. There is thus no islandwide stratigraphy of Cretaceous strata. Moreover, because the Cretaceous rocks in different nappes did not necessarily come from a single original stratigraphic sequence, there can be no valid estimate of composite thickness (such as given by Lidz, 1988). Whetten's (1966) organization of an islandwide stratigraphy showed great complexity which he attributed to facies changes that were expectable for what he correctly perceived as a turbidite realm of deposition. Our observation of fault boundaries between parcels of strata with mainly different characteristics (Table 1), however, implies the abrupt juxtapositions are tectonic, not generally depositional. Whetten's (1966) formational names, not used here, are still convenient for discussion of stratal types (i.e., Caledonia for thin bedded sandy-muddy turbidite and Judith Fancy for thick coarse lithic-rich beds) but should not be used to convey stratigraphic position. Correlations of bed sequences within nonadjacent nappes may ultimately be valid, given new dating; suggestions for such correlation by general lithic lookalikes were aptly made by Whetten (1966)—for examples, parts of nappes K2 and K6.

Depositional Ages: Fossil evidence for ages of deposition now exists from ten samples at eight sites, and a radiometric age exists for an igneous clast in sandstone at a ninth site (Table 2). Of these, only two of the eleven samples can be taken as probable age of deposition. The two are ammonites, one found as an isolated individual at the top of a distal turbidite (Perinoceras) and the other as float on a hilltop in similar beds (Tarrantoceras). Neither is associated with other fossils, and each is much larger than any associated grains. The ammonites are therefore probably pelagic. The other dated samples are resedimented and give only a maximum age of deposition. The planktic forams at sites 4 and 6 (Table 2) are considered resedimented because of their association with resedimented megafossils.

A minimum age of deposition of the Cretaceous strata is probably given by dates of the intrusive rocks (Table 2). The similarity of radiometric dates from postcomplex igneous rocks from seven sites and of petrography makes a compelling argument for nearly synchronous emplacement of such igneous bodies throughout St. Croix. No dates exist, however, for dikes in nappes K1, K4, and K6, and we must assume such dikes are also Maastrichtian. The average mean value date for

Table 1: Characteristics of Nappes in Cretaceous tectonic complex

Nappe	Lithotypes	Known Depositional Ages	Structures
K1	thin bedded graded sandy turbidite and nongraded ss, both loc. calcarenite; massive mst; minor pebbly ss with nonvolc + volc lithoclasts; ss are fsp > lith > skel > pyx	Campanian or Maastrichtian	subvertical homoclinal bedding and S1 cleavage + steep F1 fold axes; steep and flat shear zones with F2 folds, S2 cleavage, and quartz veins; late kinks
K2	thin and med bedded sandy-muddy turbidite with cherty tops; intervals of thick graded volc ss±debris flow up to 20 m thick; bedded chert; ss are fsp>>lith > pyx=skel	Cenomanian or Turonian and Coniacian	4 phases: 1) local zones of isoclines; 2) pervasive SW-verging close major and minor folds + cleavage; 3) upright macrofolds of beds + cleavage; 4) steep and flat faults + related folds and kinks
K3	massive and laminated mst, loc cherty and muddy turbidite; thick bedded graded or massive or pebbly ss; skeletal debris flow; ss are fsp > lith > pyx > skel	late Campanian or Maastrichtian	similar to K2 phases 2-4
K4	thick bedded massive or graded coarse wacke, mainly pebbly, and sed breccia; thin bedded sandy turbidite; ss are lith > fsp=pyx; loc skel-rich	late Campanian and Maastrichtian	major and minor SW-verging open or close folds with local cleavage; later faults and related local folds
K5	thick bedded graded and massive ss and sandy turbidite alternate with intervals of thin-med bedded sandy-muddy turbidite; also massive mst and debris flow; ss are lith > fsp > pyx > skel	Campanian or Maastrichtian	major upright or S-overturned folds with local cleavage; late faulting
K6	thin bedded muddy-sandy turbidite, loc with cherty tops; intervals thick graded-lam or massive ss ± pebbly ss ± debris flow; ss are fsp > lith > skel > pyx	undated	early minor folds and pervasive cleavage with SW vergence plus flattened cgls; late minor folds of bedding and cleavage

postcomplex igneous rocks is about 69 ma which is late Maastrichtian according to Kent and Gradstein (1985), and the oldest mean value is 71.8 ma, early Maastrichtian. These dates on igneous hornblende can be regarded as accurate because of fresh mineral separates and the absence of postemplacement heating or burial (Speed et al., 1979).

Dating indicates (Table 1) that nappes K1, K3, K4, and K5 contain beds of Campanian and/or Maastrichtian age, and K2 contains substantially older beds, Cenomanian or Turonian and Coniacian. K6 is undated and can only be assumed to be Maastrichtian or older. It is important to note that each nappe probably contains a thick stratal sequence, and current dating does not sample the full sequence of any nappe. The dated sites in K2 are probably low in its sequence, and because K2 is mainly thin bedded and probably not rapidly deposited, it may continue well up in the Late Cretaceous.

The time span represented by dates of the Cretaceous strata is about 28 ma at maximum (base Cenomanian to 69 ma) and about 15 ma at minimum (mid-Turonian to base Maastrichtian), using the Kent and Gradstein (1985) correlations.

Volcanigenic Lithotypes: Nearly all (>99%) of the Cretaceous sediments of St. Croix have generally related compositions: arc volcanigenic with varied minor proportions of skeletal and intraclastic debris (Table 3). Clast types outside this realm are very rare, and in particular, no sediment derived from continental or highgrade metamorphic terranes has been recognized. The volcanigenic particles were probably all derived from a region of contemporaneous volcanism, not from an ancient terrane. Whetten's (1966) distinction of tuffaceous vs epiclastic volcanigenic debris is not supported by our observations; the sediments he called epiclastic are at higher grades of in situ metamorphism, which may account for perceived mineralogical differences. A radiometrically dated volcanic clast in K3, a pyroxene-hornblende porphyry, is 75.3 ±4.3 ma (Table 2), indicating that the maximum duration of extrusion, transport, deposition, and deformation before late Maastrichtian postcomplex intrusion was about 6 ma. It is probable that extrusion and deposition were concurrent at 75 ma and that the tectonic complex took 5 or 6 ma to build up.

The only clast type suggestive of an unroofed source region is rare diorite, but these may have emerged from the volcano as inclusions in extrusions.

Table 2: Depositional ages of Cretaceous sedimentary and igneous rocks

Site[1]	Fault Packet	Basis	Age[2]	Reference
1. Buck Island	K1	coral	Campanian or Maastrichtian (max. age)	Whetten (1966)
2. Tague Bay	K2	ammonite, *Tarrantoceras*(?)	probably Cenomanian, possibly early to middle Turonian	Speed et al. (1979)
3. Romney Pnt.	K2	ammonite, *Perinoceras*[3]	Coniacian	this paper
4. Robin Bay	K3	hbl KAr on igneous clast in pebbly sandstone	75.2±4.3 ma, Maastrichtian or late Campanian (max. age)	Speed et al. (1979)
5. Vagthus Pnt.	K4	planktic forams	Campanian or Maastrichtian (max. age)	Whetten (1966)
		rudist, *Titanosarcolites*	Maastrichtian (max. age)	Whetten (1966)
		"benthic microfauna"	Maastrichtian (max. age)	Andreieff et al. (1986)
6. Diamond Keturah	K4	planktic forams	late Campanian (max. age)	Whetten (1966)
7. Judith Fancy	K5	rudist, *Barrettia* sp.	Campanian (max. age)	Whetten (1966)
8. Sugar Bay	K5	rudist, *Barrettia* sp.	Campanian (max. age)	Whetten (1966)
9. Clairmont	K5	benthic forams	Campanian (max. age)	Whetten (1966)
10. Grapetree Pnt.	—	mafic porphyry dike; hbl KAr	70.1±3.9 ma, Maastrichtian	Speed et al. (1979)
11. East Point	—	ditto	71.8±2.2 ma, Maastrichtian	Speed et al. (1979)
12. Green Cay	—	ditto	66.1±1.8 ma, Maastrichtian to early Paleocene	Speed et al. (1979)
13. Pull Point	—	Southgate pluton, hbl KAr	66.0± 3.2 ma, Maastrichtian to early Paleocene	Speed et al. (1979)
14. plutons; sites uncertain	—	3 hbl KAr dates, presumably from Fountain and Southgate plutons (Fig. 1)	mean values 69 to 71 ma	Lidz (1988)

[1] numbered sites on Figure 1

[2] radiometric-geologic time scale correlations from Kent and Gradstein (1985)

[3] identified by W. A. Cobban, written commun., 1988.

Most volcanic lithoclasts are angular but some are subrounded, indicating that residence times in the littoral or subaerial environments at the source volcanoes was generally short to vanishing. The skeletal debris is widely distributed as broken fragments in trace amounts in medium and in coarse-grained sandstone but locally concentrated as unbroken fossils in some grain- and debris flows. Such particles (Table 1) are resedimented from neritic and/or littoral environments.

The volcanic rock fragments in Cretaceous sediments throughout St. Croix have ranges of properties: color index, phenocryst/matrix ratio, pyroxene/hornblende ratio, presence of quartz, and vesicularity. Such properties may vary greatly in a given bed, but the ranges are not conspicuously different among the six nappes.

The principal lithic distinctions among the six nappes are of general particle size distribution and the nonindependent parameters of sand composition and mean layer thickness (Table 1). Thus, for example, nappes K2 and K6 ("Caledonia") are relatively fine grained (sand/mud ~1), rich in feldspar relative to other sand particles, and thinner bedded. Sandstones of these nappes contain, however, minor but ubiquitous pyroxene and/or hornblende, and volcanic rock fragments, as well as local intervals of very thick sandstone and debris flow. On the other hand, K4 and K5 are relatively coarse-grained as a whole (sand/mud >3), have more nearly equal contents of dark minerals and lithics to feldspar, and have greater proportions of thick beds. Nappe K3 is bimodal, characterized by massive mudstone and channel-filling coarse and pebbly sandstone and rarer beds of intermediate size grade. Nappe K1 has high proportions of fine sandstone and detrital carbonate compared to other nappes. K1 also has a couple of pebbly sandstones that are distinctive for their content of nonvolcanic lithoclasts: rounded radiolarite, chert, and siliceous carbonate, which do not evidently exist in other nappes.

Layer Styles and Transport Mechanisms: The Cretaceous volcanigenic sediments of St. Croix occur in a vast range of depositional unit thicknesses, from 1 cm to > 30 m. Commonly related variables are grain size distribution, sand composition (discussed above), and the existence of channeled bases. All layers are sediment-gravity flows, except perhaps for certain thick massive mudstones which might be hemipelagic. Of the sediment-gravity flows, both turbidites and nonturbidites occur in varied proportions in each nappe. We call layers turbidite if they are generally tabular, upward fining, and have two or more consecutive Bouma zonations.

Turbidites of St. Croix are of three general types:

1. muddy: these are thin-bedded, mud-rich (ss/mst 0.1 to 1), base absent and top present, nonchannelized, and have sand rarely coarser than fine-grained; examples: Lamb Point to East End section; east Butzberg.

2. thin sandy: these are thin and medium bedded, sandrich (ss/mst >1), generally base absent, top present or absent, mainly nonchannelized, have sand rarely coarser than medium-grained; examples: northern St. George quarry; Point Cudejarre, Buck Island, Allandale.

3. thick sandy: these are layers 0.5 to 3 m thick, commonly in upward-thickening sequences; they have ss/mst >5, are base present and commonly have pebbly (lithoclastic) basal zones and scoured bases; such beds may have full Bouma zonation or be top absent; intraclasts are commonly concentrated in the Tb zone; interesting Tbcbc... repetition occurs within some individual turbidites, examples: Grapetree Point, Tague Point, Hams Bluff, Crique Dam.

Nonturbidites are of widely varying types: thick mudstone, thin ungraded sandstone, thick massive sandstone, and sedimentary breccia.

Table 3: Lithic properties of Cretaceous strata

	constituent grains	granulometry	matrix-cement	rock types
SEDIMENTARY BRECCIA	**volcanic fragments:** chiefly porphyritic, occasionally equigranular basalt, pyrox. andesite, hbl-pyrox. andesite, dacite, pyrox. dacite, plag.-pyrox-chlorite rock, and altered equivalents; scoria **skeletal fragments:** rudist, bivalve, gastropod, coral **sedimentary rock fragments:** lithic-feldspar wacke and arenite, mudstone, chert; limeclasts, locally stromatolitic **mineral fragments:** framework components in microbreccia; same as in sandstone	granule to cobble size; chiefly angular; local accumulations of sub-rounded coarse fragments.	matrix is variable mixture of sand-sized particles (of types in sandstones) in coarse-grained breccia and chlorite, 10A mica, zeolite, and hydrocalcsilicate minerals; locally dominant CO3 cement.	lithic breccia lithic-feldspar microbreccia lithic-skeletal breccia/ microbreccia megabreccia (partly brecciated slump masses)
SANDSTONE	feldspar (plagioclase) pyroxene quartz lithic clasts: very fine-grained andesite, dacite chloritic rocks, chert skeletal particles hornblende	very fine-grained to coarse-grained sand; generally angular; subrounded coarse-grained sand at places	wacke: chlorite, 10A mica arenite:carbonate cement, minor clay, zeolite, prehnite	fine-grained feldspar-lithic wacke medium- to coarse-grained feldspar-pyroxene-quartz-lithic wacke ditto: arenite
MUDSTONE	variable proportions of silt- to very fine-grained sand size feldspar-quartz-skeletal particles and finer-grained chlorite, 10A mica, carbonate, and cherty quartz; abundant silica microveinlets; gradations in proportion of SiO2 between mudstone and chert.			laminated siltstone-mudstone silty (sandy) mudstone homogeneous mudstone porcellainite
CHERT	microcrystalline quartz; veinlets of calcite and quartz abundant; frequent sprinkling of silt-sized quartz (no indications they are biogenic); smears of opaque substance.			chert silty chert

Thick mudstone is either massive or vaguely laminated and may or may not include laminae of thin ungraded sandstone or chert. The mudstone is commonly organic-rich (black). We have not investigated the microstructure of such rock and are uncertain whether it is a very muddy turbidite, perhaps locally or widely homogenized by bioturbation, or it is due to hemipelagic deposition; examples are Hughes Point, Grass Point, Cane Bay, Mt. Fancy.

Thin ungraded sandstones are well sorted, fine to coarse grained, tabular, and plane-bottomed. They commonly occur in sections with muddy or thin sandy turbidites and have higher proportions of cement (carbonate, calcsilicate) and lower matrix than turbiditic sand. They are generally massive except in coarser layers where they are conspicuously cross-laminated. These were interpreted as either a product of reworking of turbidites by bottom currents or, for the coarser beds, grain flow by Speed (1974). Stanley (1988) subscribes to the first explanation. Examples are at Buck Island southshore and East End.

Thick massive sandstones are channelized deposits associated with slumps and debris flow. They are coarse grained, commonly pebbly, and may have a rude plane lamination. Nonequant particles are well aligned, indicating a fully turbulent flow. The top few percent of the layer, if present, is commonly upward fining. Examples are at Tague Point, Isaac Point, Robin Bay, Recovery Hill, and Crique Dam.

Sedimentary breccia consists partly of thick fragment-touching piles of angular lithoclasts and poorly sorted muddy-sandy matrix. These deposits are debris flows, and although locally plane and concordantly bottomed, they occur in lenticular, channelized coarse grained sedimentary sequences. Their moderate to good clast alignment and locally graded tops indicates generally fluid flows. Slumps form another type of sedimentary breccia. These consist of slabs and folded masses of intraclastic turbidite and other layer types together with lithoclasts and occur in association with debris flows and/or massive sandstone. Examples are Grass Point, Shoy Point, Tague Point, Hams Bluff, Judith Fancy, and Vagthus Point.

Layer Sequences: Upward thickening and coarsening sequences can be recognized on two scales. Gradual thickening over 100's of meters occurs at East End to Point Cudejarre, indicating progressive progradation, probably over a broad outer fan. More abrupt thickening sequences over 10's of meters, commonly culminating in channelized deposits, can be seen at Grass Point, Grapetree Bay, Cramer Park, and Crique Dam. Upward thinning sequences are less evident.

Chert and Pelagic Rocks: Aside from sediment-gravity flows of volcanigenic particles, pelagic deposits probably form the rest, a tiny fraction, of the Cretaceous strata. They are mainly in sections of thin bedded volcanigenic rocks. The evidence for pelagic constituents is inferred from the existence of bedded chert (Speed, 1974) which is the result of thorough diagenetic transformation. Chert occurs both as a layered vitreous type and as grainy rock in the top few centimeters of muddy and sandy turbidites. Vitreous chert almost certainly arose from in situ biogenic particles, although no tests have been recognized in dissolution residues (D. L. Jones, written comm., 1980) and by microscopic study. The grainy cherts are an evident replacement product and pore filling at bed tops, implying that soluble biogenic pelagic particles accumulated between successive turbidites.

Chert diagenesis occurred early in the history of the Cretaceous sediments because 1) it is cut by sandstone dikes, 2) it occurs in intraclasts in channelized deposits, and 3) chert-rich zones took up displacements by buckling in the first deformation whereas other stratal types deformed without flexing, probably by pore volume loss.

Examples of chert are at Cramer Park and Buck Island.

Sand Loading and Intrusion: The Cretaceous rocks of nappes K2, K3, and K6 contain remarkable loading features, called linear load casts by Speed (1974) and Speed et al. (1979), and abundant sandstone intrusions occur throughout.

Linear load casts are highly elongate protrusions of the bases of sandstone layers into subjacent mudstone, in association with flame structures of mudstone. They differ from standard loads which are equant in the bedding plane, by their axiality and parallelism (Fig. 2). They are postdepositional (not flutes) because they deform lamination in subjacent layers. Moreover, they are related to tectonic deformation because axial plane cleavage parallels the bisecting plane of the linear loads and flames and tectonic fold axes parallel the linear load axes (Fig. 2). These are interpreted (Speed, 1974) to have arisen during layer-parallel tectonic compression when sands were incompressible but incohesive and mudstone was contractable by cleavage development and pore collapse. The vertical exchange of sand and mud in planes normal to maximum compression permitted the sand layers to shorten without detachment from adjacent mudstone. The upshot of this is that tectonism and cleavage development began in nappes K2, K3, and K6 before lithification of at least the basal parts of many sandstones. Examples of linear load casts are at Coakley Bay, Romney Point, Grapetree Point, and Caledonia Quarry.

Sandstone dikes and irregular intrusions occur widely in St. Croix. Such bodies transferred coarse sand fractions up or down from a sand source beds. Sandstone dikes intruded before, during, and after cleavage development, but there is no evident dike alignment relative to strain axes. Interesting sandstone phacoliths occur in folds at places where sand intruded hingeward during folding. As with linear load casts, sand intrusions indicate some sands remained unlithified through at least early tectonism. Examples of intrusions are at Cramer Park, Vagthus Point, and Judith Fancy.

Depositional Realm: Because all the Cretaceous nappes of St. Croix contain turbidites with marine skeletal particles, a general environment of deposition can be established as marine and subwavebase. The absence of planktic calcareous fossils, except at Vagthus Point and Diamond Keturah (Whetten, 1966), suggests the depth was below the carbonate compensation depth, assuming that cherts came from siliceous plankton and that diagenesis was not the cause for the near-absence of calcareous tests. Moreover, the planktic forams at the two exceptional sites are probably resedimented, as discussed earlier, and thus were buried too rapidly for dissolution in deep ocean water. The occurrence of intraclasts and slumps of turbiditic and other layers in channel filling beds and turbidites above channel fills implies the channels formed in the same deep water environment.

It is generally convenient and useful to relate such layer sequences to model turbidite fan facies (for example, Walker, 1984). We do not infer, however, that the Cretaceous rocks of St. Croix occupied any particular original fan geometry, and it is possible they may never have occupied a single initial stratigraphic succession.

The turbidite layers occur in greater or lesser abundance in all nappes. These are probably outer fan or fan fringe facies because of their tabularity and lateral continuity (where this can be seen such as at East End) and intervals of upward thickening that imply source progradation without erosion. The variations about the outer fan theme differ to degrees among nappes. Nappes K2 and K6 ("Caledonia") are principally outer fan deposits that include sporadic thick channel fills (10->50 m) which were emplaced and covered by thin turbidites. This indicates that the channeling was not due to systematic migration or reconfiguration of the fan system.

K1 has facies with abundant discrete fine sand and mud which may represent either or both bottom current reworking and interchannel plus crevasse splay deposits. The fineness of grain and paucity of sedimentary structures in such rocks may suggest the former, and the association with channelized pebbly sandstone and carbonate grain flows, the latter.

In K3, the abundant nonturbidite (?) mudstone and thick channel filling sequences suggest either an upper fan interchannel regime or fan-abandonment facies with sudden reactivation.

Nappe K4 may contain midfan and upperfan channel mouth deposits together with outer fan intervals (Whetten's (1966) Recovery Hill member). K5 has outer and midfan facies in western outcrops and upperfan channel deposits at Clairmont and Judith Fancy.

The provenance of sediment in the sediment-gravity flow deposits was an active, emergent island arc with volcanic edifices emitting magmas of varied composition, from basalt to dacite, and with neritic and/or littoral carbonate banks that flanked parts of the volcanic edifices. The source terrane is known to have supplied sediment for at least 14 ma and perhaps 30 ma or longer.

Whetten's (1966) interpreted flow directions in St. Croix turbidites as southerly. Our measurements, corrected for tectonic rotation, however, indicate varied directions and dispute claims to any preferred direction. All such measurements must take into account steeply plunging fold axes (to 60°) whose axial trends vary with position (Speed, 1974). Thus, the sedimentology of the Cretaceous rocks does not indicate the source-basin direction.

The fan facies of the Cretaceous strata suggest a basin floor rather than a slope as the general depositional site because of the general preponderance of turbidites and rarity of rocks typical of slopes such as mudslumps, pebbly mudstone, and channellized fine-grained sandstone. The basinal site was probably close to base of slope as implied by innerfan and fan-channel facies.

Tectonic Setting of Basin: The basinal sites were evidently in the vicinity of an active Late Cretaceous island arc. Three general settings can be envisioned: fore-, back, and intra-arc. The expected stratal and structural products for deposits in such settings differ as follows.

In case of a forearc, the basinal site was likely to have been an unfilled bathymetric trench because the width of the forearc was probably narrow and arc-derived sediment funneled directly to the slope base, as in Pacific arcs. Evidence suggesting a narrow forearc is the lack of continental sediments and the absence of pelagic carbonate beds which might imply deposition above CCD in a forearc basin or slope basins on a wide forearc. The exception to an exclusively volcanigenic and fringing reef-derived sediment population is the clasts in pebbly sandstone of nappe K1 (Buck Island) which indicates unroofed radiolarian pelagic rocks; these were perhaps resedimented within the forearc. In a trench, fan facies would have developed a complex pattern by flow parallel to and across the trench axis (for example, Graham et al., 1975; Schweller and Kulm, 1978). Further, most sediments deposited in a trench would have probably accreted within a few million years of their accumulation. Therefore, accretion (imbrication and folding) and sedimentation were continuing and contemporaneous phenomena, and strata in adjacent imbricate sheets would not generally have been in a single initial stratigraphic succession.

A backarc basin site, on the other hand, would probably have been tectonically relatively stable during sediment accumulation. A vertical succession of strata in radial fans (Walker, 1984) would be predicted. Then, the onset of a phase of tectonic activity, not specifically predicted by plate tectonic theory, is required to have imbricated the succession. Such activity can be envisioned as a Maastrichtian subduction of backarc basin lithosphere below the arc, in which case the arc-trench system would have been N or NE facing in today's coordinates.

An intraarc basin occurs within the magmatic arc platform, probably steep-walled graben caused by extension that accompanies arc-building. Deposits in such basins are probably like those in backarc basins but with sediment sources from both sides of the graben. Beds deposited in an intraarc basin might be expected to include calcareous pelagic rocks unless the rate of turbidite accumulation were too great to permit discrete pelagic deposits. A major distinction between intraarc and backarc or trench/forearc basins is the much greater probability of magmatism during sedimentation.

Several observations suggest a forearc site is the more likely. First, the imbricate sheets do not repeat an evident stratigraphic succession. Second, the imbrication and deformation of Cretaceous strata in nappes K1, K3, K4, and K5 occurred shortly after their deposition (0-10 ma) and the sand mobility in all nappes indicates incomplete lithification before imbrication. In contrast, the intrusion of sills and dikes in at least two and probably more stages within the Late Cretaceous suggests an intraarc basin may have been more likely.

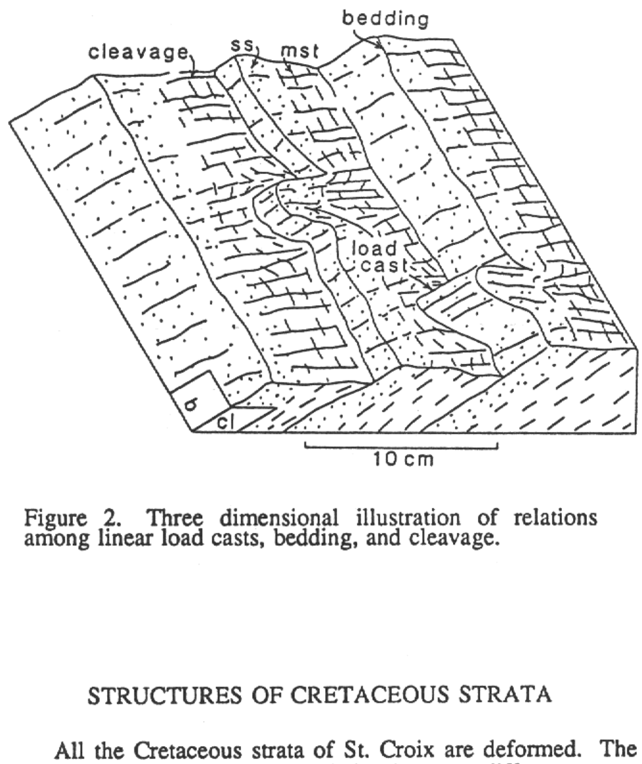

Figure 2. Three dimensional illustration of relations among linear load casts, bedding, and cleavage.

STRUCTURES OF CRETACEOUS STRATA

All the Cretaceous strata of St. Croix are deformed. The structures and their sequence of development differ nappe to nappe, but certain common elements exist among nappes. Each nappe underwent at least one phase of deformation before the youngest phase (postcomplex) of igneous intrusion in the Maastrichtian (66-72 mybp). The timing of some later phases of deformation relative to intrusion is uncertain.

Table 4 summarizes principal structures in sequence for nappes K1-6.

Table 4: Structures in sequence in Cretaceous nappes
(sequence numbers not necessarily correlative nappe to nappe)

Nappe	
K1	D1: subvertical to overturned homocline, E striking and S facing; foliation (S1) steeply N dipping; tight minor folds (F1) with axial planes in foliation plane and N verging; homocline probably a flank of a S verging major fold. D2: flat and steep fault zones with central shear zones with foliation and quartz veins; open to tight folds of bedding and S1 in shear zone walls; folds are mainly flat, some doubly hinged.
K2	D1: local isoclines in chert-rich sections, folded nearly homoaxially by F2 folds; detached from adjacent strata. D2: pervasive close S verging major folds (F2) with axial plane cleavage (S2) and trains of harmonics with vergence appropriate to limb position; axial planes dip between N and W (folded in D3); F2 axes plunge steeply in S dipping great circle. D3: major folds of D2 elements; D3 axial traces defined mainly by formlines of D2 cleavage (Fig. 4); D3 axial planes strike ENE, dip 70°S to 90° (Fig. 4); rotation of F2 axes in D3 suggests horizontal maximum elongation. D4: late fault-related folds and kinks. Orientation data for K2 in Speed (1974).
K3	D1: isoclinal folds in pelitic rocks with strong axial plane cleavage, dipping between N and W, and major S verging folds of thick layer sequences. D2 and D3: same as D3 and D4 of nappe K2.
K4	D1: sporadic close major and macroscopic folds with S vergence or overturning; local S1 axial plane cleavage in muddy beds, poorly developed; cleavage and folds with varied orientation suggest D2 event and rotation of cleavage about a N plunging axis.
K5	D1: sporadic cleavage in muddy rock; dips between N and E, modally NE. D2: major close folds (Fig. 1) with WNW striking, steeply N dipping axial planes, and S overturning; F2 axes plunge steeply E.
K6	D1: minor folds with axial plane cleavage (S1) dipping NNE to NE; F1 axes plunge ENE; sedimentary breccia flattened in cleavage plane (NE dip) and X/Y = 1 to 3, X (max. elongation) N plunging. D2a: minor chevron and kink folds of bedding and cleavage; S2 axial planes conjugate, dip N and S; F2 axes steeply E plunging. D2b: major gentle syncline with WNW axial trace (Fig. 1), probably continuous with D2 syncline of K5.

Major Features: Beds in all the nappes are in early folds with harmonic content that varies with layer thickness implying a buckling rather than fault-bend origin. The number of fold superpositions varies among nappes; most have two, but K2 has four. Axial planes and related cleavage all had initial strikes between E and NE and northerly dips. Vergences of major folds are southerly in all nappes. Axes of all folds plunge easterly, generally between 30° and 70°; except for some reoriented early folds.

Cleavage occurs in all nappes, but its development varies. It is strongly developed in the structurally lower nappes (K1, K2, K3, K6) which are more generally muddy. There, it is closely spaced and pervasive and at least partly a product of pressure solution. Its occurrence is more sporadic in higher nappes (K4, K5), even in muddier intervals. This seems to reflect initial development rather than degree of contact metamorphic obscuration. Structural depth may have been the controlling parameter to cleavage development.

No penetrative tectonic lineations have been recognized in St. Croix, implying strains were flattening rather than constrictional. This is supported by clast shapes in strained sedimentary breccias where X/Y = 1 to 3 within the cleavage plane.

Late major folds have been superposed on earlier fold sets in at least four nappes (K2, K3, K5, K6). These have approximately E striking axial planes with steep dips. They are discussed further below.

Late brittle faults and related folds and kinks in their walls affect all the nappes. Their orientations and slip sense are highly varied: normal-oblique, reverse, thrust, and horizontal. They probably formed in several stages and almost certainly are not all synchronous. Some normal faults were clearly contemporaneous with Maastrichtian diking and are followed by dike tips and diatremes. At the East End, such faults indicate ENE-WSW horizontal extension during diking. It is probable that some sets of late faults are related to the central graben of Cenozoic age (Fig. 1).

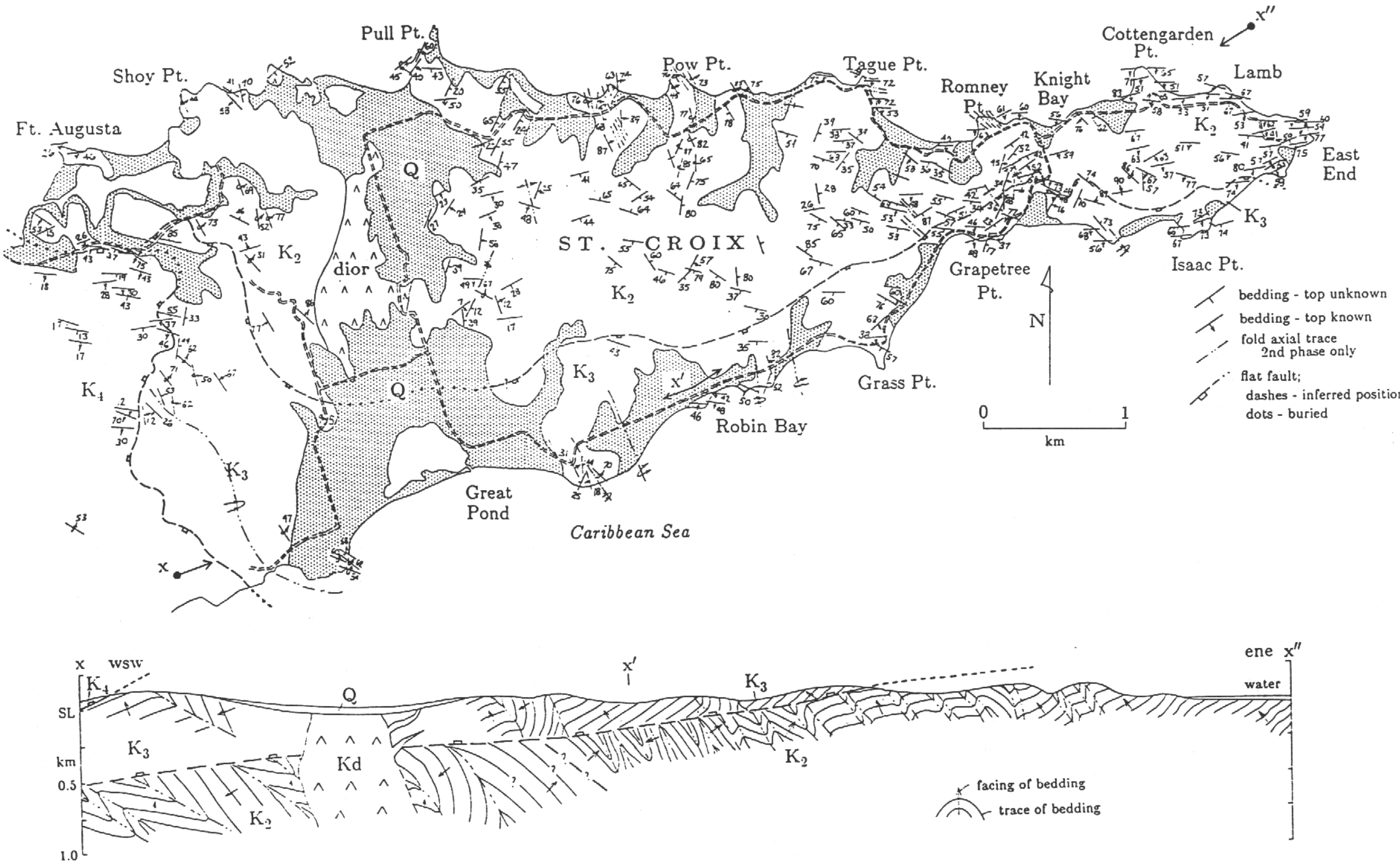

Figure 3. Map and section of eastern St. Croix showing distribution of bedding attitudes, approximate nappe boundaries, and axial traces of folds of most intense deformation phase (phase 2 in K2, phase 1 in K3).

East End Structures: Figure 3 shows a map of bedding and cross sections for eastern St. Croix. The principal features are the south to west vergent folds of nappes K2 (F2) and K3 (F1) where exposures permit them to be identified.

Because both nappes possess the same fold train, they were either 1) juxtaposed before this folding event or 2) folded at different sites under the same kinematic regime and then juxtaposed without rotation. At the three places where the K2-K3 boundary is exposed, the fault cuts cleavage, implying the fault is younger than this fold train. Therefore, the second explanation has support.

Figure 4A shows the orientations of cleavage related to the principal folding of K2 (S2) and K3 (S1), together with form lines to assess axial trace orientation of late major folds that cause the 90° variation in cleavage strike. Figure 4B (Equal area net lower hemisphere) shows that poles to cleavage form a girdle with easterly plunging axis. Figure 4C shows that the constructed axial plane for the late major fold is ENE striking and steeply dipping.

The emplacement of nappe K4 on K3 and K2 was after the early deformations of the lower nappes (D2 in K2, D1 in K3) because the boundary cuts their cleavage. It is unclear whether the late major folds affect K4 or not.

West End Structures: Figure 5 shows structural data and interpretation for a part of western St. Croix from our field studies, chiefly by J. Joyce, together with some bedding attitudes from Whetten (1966). The position of the K5-K6 fault boundary is interpolated among three exposures at Cane Bay, Annaly Trail, and near Oxford.

The lower nappe, K6, contains two deformation phases (Table 4). The first includes minor folds, F1, and axial plane cleavage, S1, from the northern coast to Sprat Hall (Fig. 5). Poles to S1 occupy a short girdle whose maximum plunges SW. The F1 axis maximum plunges steeply ENE. South of Sprat Hall, K6 may include the vertical or overturned limb of a major F1 fold (section, Fig. 5). F2 folds in K6 have E striking axial planes; these are not included on the section of Figure 5 because their occurrence is sporadic and amplitude small.

The upper nappe, K5, contains major folds of bedding and sporadic local cleavage (Table 4). Because the major folds' axial planes (WNW strike, steep NNE dip) are not apparently coplanar with cleavage (NW strike, moderate NE dip) (Fig. 5), the two structures are provisionally considered to be sequential. Although the data are sparse, owing to limited exposure, cleavage seems not to be folded; hence, the major folds are taken as D1 and cleavage, D2.

The K5-K6 boundary was an active fault during and/or after D1 of K6 because S1 cleavage is deflected at the boundary. The nappe boundary was also active during D1 of K5 because it partly cuts out the major fold limbs (Fig. 5). The nappe boundary and homoclinal bedding of K6, however, are in low amplitude folds with axial traces approximately coincident with those of D1 folds in K5. This implies that K5 and K6 locked together before the cessation of folding in K5. Perhaps, D2 deformations in both nappes are a further response to contraction after nappe locking.

Timing of Structures: In eastern St. Croix, the juxtaposition of nappes K2 and K3 and deformations D1+2 in K2 and D1 in K3 occurred before latest Maastrichtian intrusion. Evidence includes cutting of structures by undeformed dikes and contiguity of the area of strong contact metamorphism by the Southgate pluton (Fig. 1) across the nappe boundary. The age of late major folding (D3 in K2, D2 in K3), however, is unknown within the range, Maastrichtian - early Miocene. The range is supplied by D1 in K3 and earliest known ages of little deformed cover to the Cretaceous of St. Croix. The intrusions do not date the late folding because such folds have large wavelengths and the dikes had no uniform initial attitude.

The age of juxtaposition of nappe K4 is unconstrained after rock deposition in the Maastrichtian. Until disputed by new evidence, we assume it to have been during the Cretaceous as with K2 and K3. A plausible alternative, however, is that the base of K4 is a Cenozoic low-angle normal fault related to tectonics that caused the central graben of St. Croix.

In western St. Croix, D2 (cleavage) of K5 and D1 of K6, hence juxtaposition of K5 and K6, preceded intrusion and are probably of Maastrichtian age. The key evidence is that metamorphism in dike walls is postcleavage in both nappes, but use of this to date cessation of relative movement of the nappes pivots on the argument that cleavage of K5 is contemporaneous with or later than cessation. The age of D2 in K5 is unconstrained.

Structural Evolution: The principal structures of the Cretaceous strata of St. Croix, nappes, early folds, and foliation provide evidence for contraction and imbrication in Late Cretaceous time, probably mainly or entirely Maastrichtian. Such deformation can be interpreted as a product of thrust imbrication even though the ages across nappe boundaries are unknown.

Because the imbrication took place at or near the base of slope of an island arc, the displacement zone was almost certainly a convergent plate boundary. The thrust stacking accreted sediment sheets to the front of an overriding plate from a downgoing one. The pervasive SW to S vergence and/or overturning of structures within the imbricated sheets implies the downgoing plate had a component of Late Cretaceous relative motion between N and NE in today's coordinates. The late folding in nappes K2 and K3 can be interpreted as representing progressive NS shortening of the imbricated sediments after accretion.

The relationships of Cretaceous strata before imbrication are unclear. The lack of stratigraphic correlations among adjacent nappes indicates either that 1) the strata were sequentially deposited and accreted, as in a trench wedge, or 2) that both emergent thrusting and duplexing occurred in an initially continuous stratigraphic sequence.

Tectonics: Current understanding permits two alternative schemes for the early tectonic evolution of St. Croix's Cretaceous tectonic complex. First is the deposition of Late Cretaceous volcanigenic strata on a trench floor to the present south and west of the magmatic arc platform. Such strata were progressively driven into and scraped off at the toe of the island arc's accretionary prism. This hypothesis accounts well for the structure and stratigraphic differences of nappes. It suffers, however, in the attempt to explain two or more phases of magmatism within the basin during and after sediment accumulation and deformation.

Second is the deposition of the Cretaceous strata in an intraarc basin which collapsed in Maastrichtian time. Basin collapse may have had vergence either toward the fore- or backside of the arc or conceivably was bivergent. Therefore, an intraarc basin origin provides no implications for arc polarity. An intraarc basin origin is supported by the intrusion of Late Cretaceous arc magmas into the basinal strata before and after deformation. Such an origin may be disputed, however, by the lack of carbonate pelagic beds.

To conclude, origins of Cretaceous sediments as trench fill or intraarc basin deposits are currently permissible. Further studies are required to discriminate these origins.

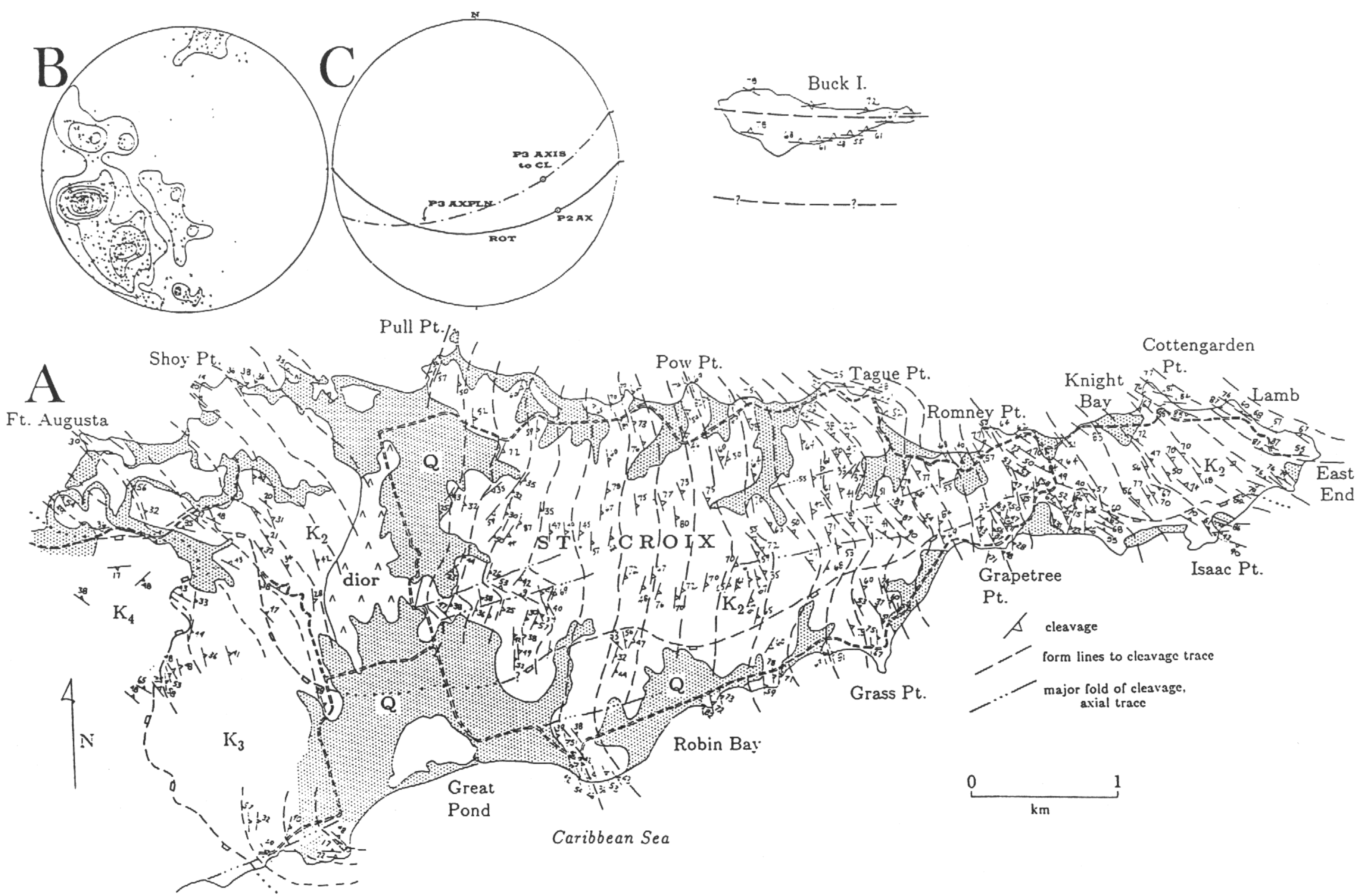

Figure 4. Map of eastern St. Croix showing distribution of cleavage attitudes and axial traces of some late stage macroscopic folds of cleavage (phase 3 in K2, phase 2 in K3). Orientation diagrams (equal area, lower hemishpere): B) poles to cleavage (x) and axial planes (dots) that are phase 2 in K2 and phase 1 in K3; C) calculated axial plane (dash-dot line) for late stage (phase 3) macrofolds from average axial trace (map) and axis to elements in B; solid great circle is rotation path of phase 2 fold axes.

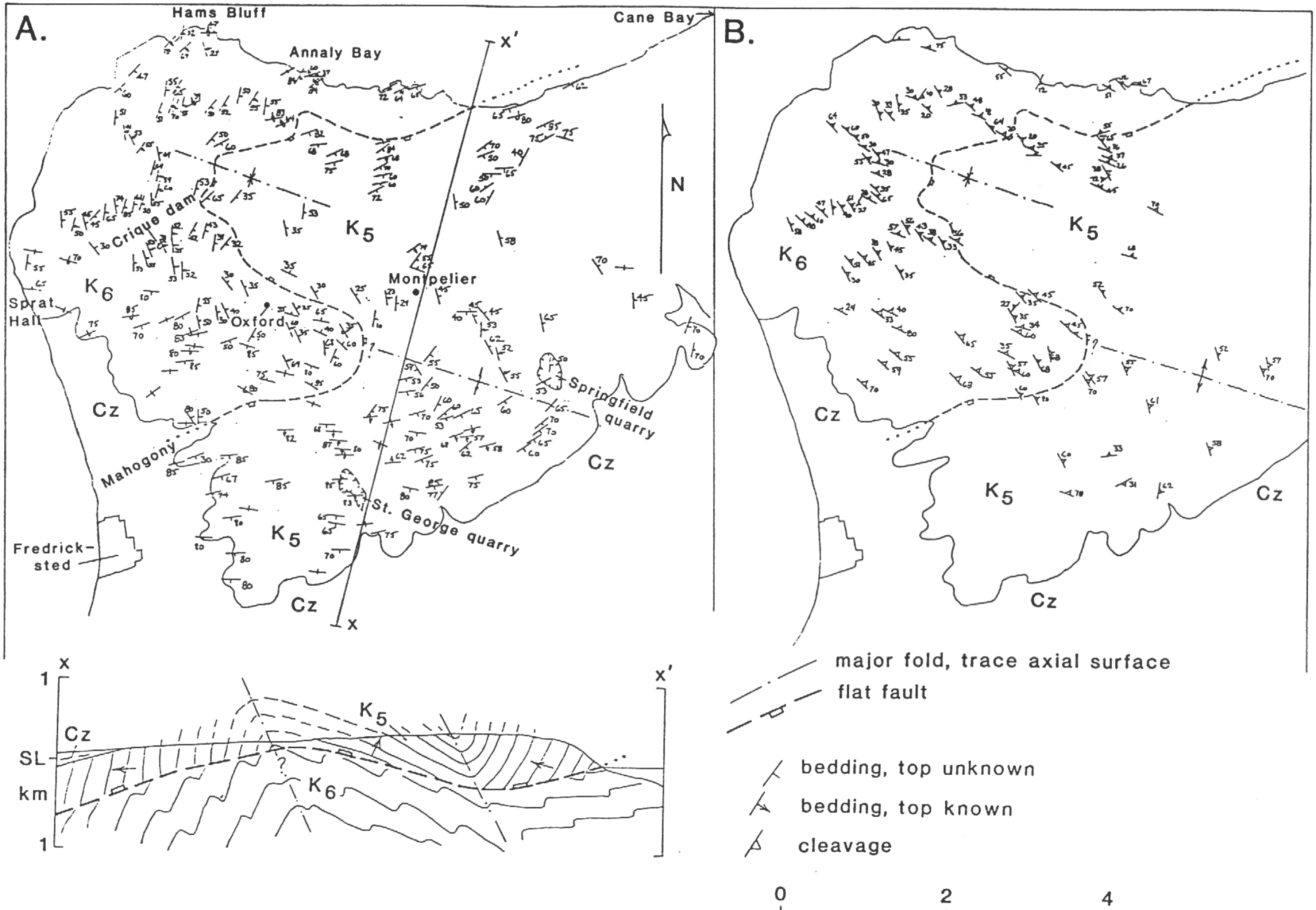

Figure 5. Maps of Northside Range, western St. Croix; A) bedding and phase 1 macroscopic fold axial traces; shows trace of cross section xx'; B) same map showing cleavage that is probably second phase.

CONCLUSIONS

1. The exposed sub-Cenozoic rocks of St. Croix are deep marine volcanigenic sedimentary rocks with minor pelagic interbeds. Their depositional ages range from Cenomanian or Turonian to Maastrichtian. There are no magmatic rocks, but the volcanigenic constituents came from an active island are throughout this duration.
2. The Cretaceous strata occupy a tectonic complex that probably comprises thrust-bounded sheets (nappes). No islandwide stratigraphic succession exists.
3. The Cretaceous strata are in outer to innerfan facies. They were deposited at or near the base of slope of a Late Cretaceous island arc. The basin was probably a trench adjacent to the convergent boundary of the island arc system or a basin (intraarc) within the magmatic arc platform.
4. Island arc magmatism at the sediment source was ongoing for at least 14 ma and perhaps, more than 30 ma.
5. Imbrication of the Cretaceous strata was accompanied by folding and cleaving with vergence or overturning between S and SW in today's coordinates. The imbrication was followed by later NS horizontal contraction.
6. Imbrication was completed in Maastrichtian time. It is interpreted as representing the accretion of sediment to the forearc toe above a downgoing plate with a component of N to NE transport relative to the island arc or the collapse of an intraarc basin with either fore- or back-thrusting.

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